

# Revisiting Metallicity of Long Duration Gamma-Ray Burst Host Galaxies: The Role of Chemical Inhomogeneity within Galaxies

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## ABSTRACT

We predict the metallicity probability distribution function (PDF) of long gamma-ray burst (GRB) host galaxies at low-redshifts ( $z \lesssim 0.3$ ) when GRBs occur only in low-metallicity environment, assuming empirical formulations of galaxy properties. We discuss contribution of high-metallicity galaxies to the cosmic rate of low-metallicity GRBs, taking internal dispersion of metallicity within each galaxy into account. Assuming GRBs trace low-metallicity star formation  $< Z_{\text{crit}}$ :  $12+\log_{10}(\text{O}/\text{H}) = 8.2$ , we find that GRB host galaxies may have systematically higher-metallicity than that of GRB progenitors. Furthermore, we expect  $\gtrsim 10\%$  of the host galaxies to have  $12+\log_{10}(\text{O}/\text{H}) > 8.8$ , if galaxies have internal dispersion of metallicity comparable to that observed in the Milky Way. Our results show that the low-metallicity scenario of GRB progenitors can be reconciled with the recent discoveries of the high-metallicity host galaxies of GRBs. We also show possible bimodality in the host metallicity PDF that results from the single progenitor model of GRBs. If found in future observation, the bimodality can be a clue to constrain the nature of GRB progenitors.

**Key words:** gamma-ray burst: general – galaxies: abundances.

## 1 INTRODUCTION

It is now broadly agreed that some of long gamma-ray bursts (GRBs) originate in core-collapse supernovae (CC SNe). However, not all CC SNe produce GRBs, and the criteria that discriminates GRBs from general CC SN is one of the most outstanding questions about GRBs.

Some theoretical studies on the origin of GRBs using stellar evolution models suggest that a low-metallicity may be a necessary condition for a GRB to occur ( $Z < \text{a few} \times 0.1Z_{\odot}$ , e.g., MacFadyen & Woosley 1999; Yoon & Langer 2005; Yoon et al. 2006; Woosley & Heger 2006). It has also been suggested from observations that metallicity distribution of GRB host galaxies at redshift  $z < 0.25$  is significantly biased towards low metallicities compared to the expectation when GRBs are unbiased tracers of star formation (Stanek et al. 2006; Modjaz et al. 2008).

Furthermore, some observations suggest that the GRB host galaxies are systematically fainter and smaller than those of the core-collapse SNe (Le Floc'h et al. 2003; Fruchter, et al. 2006; Svensson et al. 2010), indicating that the GRBs may preferentially occur in low metallicity environment, because fainter and lower mass galaxies gener-

ally have lower metallicities. These interpretations have also been supported by other theoretical studies using the models of galaxies (e.g. Wolf & Podsiadlowski 2007; Niino et al. 2011).

However, recent discoveries of high-metallicity host galaxies of some GRBs cast doubt on the requirement of low-metallicity in GRB occurrence (Levesque et al. 2010a,b; Han et al. 2010; Hashimoto, et al. 2010). On the other hand, it should be kept in mind that GRB host galaxies may have different metallicity from that of GRB progenitors, because a galaxy is not a chemically homogeneous object. To decide whether the discoveries of the high-metallicity host galaxies are consistent to the low-metallicity requirement or not, we need to quantitatively consider contribution of high-metallicity galaxies to the cosmic rate of low-metallicity star formation.

In this study, we predict the metallicity probability distribution function (PDF) of GRB host galaxies at  $z \lesssim 0.3$ , assuming the low-metallicity requirement and taking the metallicity dispersion within each galaxy into account. We discuss whether the expected rate of low-metallicity GRBs in high-metallicity galaxies is significant to explain the observations or not. We use empirical formulations of galaxy properties, and assume GRBs trace low-metallicity star formation  $< Z_{\text{crit}}$ :  $12+\log_{10}(\text{O}/\text{H}) = 8.2$ . In § 2, we describe

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empirical formulations of galaxy properties and GRB rate models which we use in this study. In § 3, we show the expected metallicity and mass distributions of GRB host galaxies and discuss their implications. In § 4, we also discuss how the expected metallicity distribution changes if there is a correlation between metallicity and star formation rate of a galaxy, as it is claimed in Mannucci et al. (2010). We summarize our conclusion in § 5.

## 2 MODELS

### 2.1 Galaxy Properties

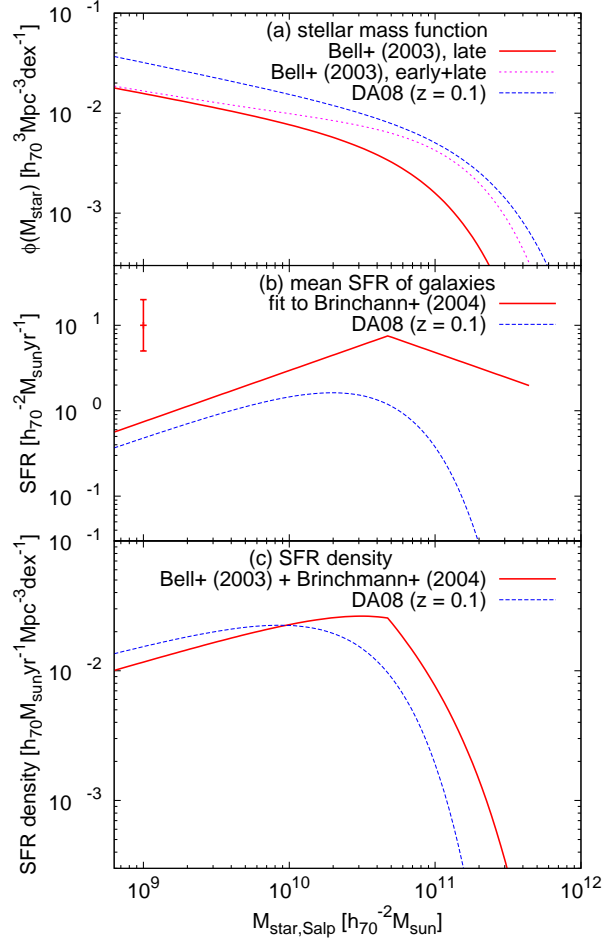
To compute the expected metallicity PDF of GRB host galaxies at  $z \lesssim 0.3$ , we assume empirical formulation of stellar mass function, mass–star formation rate ( $M_\star$ –SFR) relation of galaxies, and mass–metallicity ( $M_\star$ – $Z_{\text{gal}}$ ) relation of low-redshift galaxies. Our approach is similar to that of Stanek et al. (2006), who have calculated expected metallicity PDF of GRB host galaxies when GRBs trace star formation without any metallicity dependence. However, we step further to include the low-metallicity preference of GRBs considering the chemical inhomogeneity within galaxies.

It should be noted that  $M_\star$  is calibrated using different initial mass functions (IMFs) in different studies. In this study, we assume conversion among stellar mass scales for different IMFs as:  $M_{\text{Salpeter}} = 1.43 \times M_{\text{dietSalpeter}} = 1.5 \times M_{\text{Kroupa}} = 1.8 \times M_{\text{Chabrier}} = 1.8 \times M_{\text{BG03}}$  (Salpeter 1955; Bell & de Jong 2001; Kroupa & Burkert 2001; Chabrier 2003; Baldry & Glazebrook 2003). Hereafter stellar masses are scaled for Salpeter IMF, unless otherwise stated.

We use empirical formulations of the stellar mass function (Bell et al. 2003), and the  $M_\star$ –SFR relation [Stanek et al. (2006), a fit to the observation by Brinchmann et al. (2004)] of low-redshift ( $z \lesssim 0.3$ ) late-type galaxies. We assume the dispersion of the  $M_\star$ –SFR relation to be  $\sim 0.3$  dex following Stanek et al. (2006). Using the mass function and the  $M_\star$ –SFR relation, we compute cosmic SFR density as a function of  $M_\star$ :  $\rho_{\text{SFR}}(M_\star)$  [ $M_\odot \text{yr}^{-1} \text{Mpc}^{-3} \text{dex}^{-1}$ ]. These models are shown in Fig. 1. We only consider galaxies with  $\log_{10} M_\star > 8.0$ , which corresponds to the lowest-mass of GRB host galaxies ever known. Both of the stellar mass function and the  $M_\star$ –SFR relation may suffer from selection effects of the galaxy sample. To demonstrate the uncertainty, we also use  $\rho_{\text{SFR}}(M_\star)$  derived from observation of galaxies of all-type (Drory & Alvarez 2008, DA08).

Various methods have been proposed to measure gas metallicity of galaxies, but they do not always agree with each other (e.g., Kennicutt et al. 2003; Kewley & Ellison 2008). When we discuss metallicity of galaxies, we use metallicities calibrated with Kobulnicky & Kewley (2004, hereafter KK04) method in this study. We use the  $M_\star$ – $Z_{\text{gal}}$  relation with the KK04 calibration presented in Eq. 8 of Savaglio et al. (2005, hereafter S05 relation). We assume the dispersion of the relation to be 0.1 dex (Tremonti et al. 2004).

When we consider the dispersions of  $M_\star$ –SFR relation and  $M_\star$ – $Z_{\text{gal}}$  relation, we assume that the offset from  $M_\star$ – $Z_{\text{gal}}$  relation and that from  $M_\star$ –SFR relation are independent of each other. This assumption is supported by the

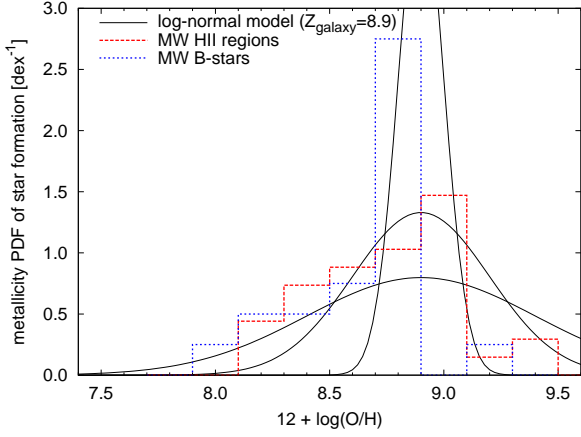


**Figure 1.** Empirical formulations of stellar mass function,  $M_\star$ –SFR relation, and SFR density for late-type galaxies (Bell et al. 2003; Brinchmann et al. 2004). Those for all types of galaxies (DA08) are plotted together. In panel (b), the typical dispersion of galaxy SFR around the relation is shown.

observed no correlation between  $H\alpha$  equivalent width and SFR (Tremonti et al. 2004). However, it is also claimed that those offsets are correlated (Mannucci et al. 2010), and we discuss the case where the offsets are correlated in § 4.

### 2.2 GRB Rate and Internal Dispersion of Metallicity within Each Galaxy

Observations of nearby galaxies, including the Milky Way (MW) and the Magellanic clouds, show that the galaxies have internal dispersion of metallicity within them ( $\sim 1$  dex in MW and  $\sim 0.3$  dex in the Large Magellanic Cloud (LMC), e.g., Rolleston et al. 2000, 2002). Furthermore, there is a  $\sim 0.4$  dex variation of  $12+\log_{10}(\text{O}/\text{H})$  among HII regions in the host galaxy of GRB 980425/SN 1998bw which is comparable to  $3\sigma$  error of the metallicity calibration (Christensen et al. 2008). To demonstrate effects of the chemical inhomogeneity, we assume metallicity of SFR in a galaxy has a log-normal distribution with dispersion  $\sigma_{Z,\text{int}}$  around  $Z_{\text{gal}}$ , al-



**Figure 2.** The log-normal models of the internal metallicity dispersion within a galaxy is shown ( $\sigma_{Z,\text{int}} = 0.1, 0.3$  and  $0.5$ , solid curves), together with the metallicity distributions of the HII regions and the young B-type stars (Afflerbach et al. 1997; Rolleston et al. 2000, red dashed and blue dotted, respectively). We note that the metallicities measured in Afflerbach et al. (1997) and Rolleston et al. (2000) may be inconsistent with KK04 metallicities.

though metallicity distribution of star forming gas within a galaxy is hardly understood.

In Fig. 2, we plot the log-normal models with  $Z_{\text{gal}} = 8.9$  and  $\sigma_{Z,\text{int}} = 0.1, 0.3$  and  $0.5$ . For comparison, we plot the observed metallicity distribution of HII regions and young B-type stars in the MW (Afflerbach et al. 1997; Rolleston et al. 2000) together, although they do not necessarily represent overall metallicity PDF of star forming gas in the MW. Both of the HII regions and the B-type stars typically have  $12 + \log_{10}(\text{O}/\text{H}) \sim 8.9$ , while  $\sim 10\%$  have  $12 + \log_{10}(\text{O}/\text{H}) \lesssim 8.2$ , which is roughly comparable to the case of  $\sigma_{Z,\text{int}} = 0.5$ . Although the models and the observation do not agree with each other in the high-metallicity end, we note that the high-metallicity end of the internal metallicity distribution has small effect on our results.

In this study, we assume GRB rate is proportional to low-metallicity SFR with  $Z < Z_{\text{crit}}$ , and express  $R_{\text{GRB}} \propto \epsilon_{\text{GRB}}(Z_{\text{gal}}) \times \text{SFR}$ , where  $\epsilon_{\text{GRB}}(Z_{\text{gal}}) \equiv \text{SFR}_{Z < Z_{\text{crit}}} / \text{SFR}$  is a GRB efficiency in a galaxy. We do not need to determine the proportionality constant, because our interest is in the metallicity PDF of GRB host galaxies. Under the assumption of the log-normal metallicity distribution, the GRB efficiency can be written as:

$$\epsilon_{\text{GRB}}(Z_{\text{gal}}) = 0.5 \times \text{erfc}\left[\frac{-\log_{10}(Z_{\text{crit}}/Z_{\text{gal}})}{\sqrt{2}\sigma_{Z,\text{int}}}\right]. \quad (1)$$

Here we assume  $Z_{\text{crit}}$  to be  $12 + \log_{10}(\text{O}/\text{H}) = 8.2$ , which roughly corresponds to  $0.2\text{--}0.4Z_{\odot}$ . The expected metallicity distribution of GRB host galaxies is  $\hat{\rho}_{\text{GRB}}(Z_{\text{gal}}) \propto \epsilon_{\text{GRB}}(Z_{\text{gal}}) \hat{\rho}_{\text{SFR}}(Z_{\text{gal}})$ , where  $\hat{\rho}_{\text{SFR}}(Z_{\text{gal}})$  is the  $\rho_{\text{SFR}}(M_{\star})$  projected to  $Z_{\text{gal}}$  axis using the  $M_{\star}\text{--}Z_{\text{gal}}$  relation.

It should be noted that Kocevski et al. (2009) performed similar investigation to that in this study to calculate the mass PDF of GRB host galaxies when GRBs trace low-metallicity SFR, and claimed  $Z_{\text{crit}} > 0.5Z_{\odot}$  which is contrary to our assumption. However, they assumed that  $R_{\text{GRB}} = 0$  when  $Z_{\text{gal}} > Z_{\text{crit}}$  without taking the internal dis-

persion of galaxies into account, and their conclusion might be affected by this assumption.

### 3 THE METALLICITY PDF OF GRB HOST GALAXIES

The predicted metallicity PDF of GRB host galaxies is shown in the left panels of Fig. 3. The model without metal cutoff (i.e.  $\epsilon_{\text{GRB}}(Z_{\text{gal}}) = 1.0$ ) is consistent to the results of Stanek et al. (2006), and it shows that more than 50% of low-redshift star formation takes place in high-metallicity galaxies with  $12 + \log_{10}(\text{O}/\text{H}) > 8.8$ , which is much higher fraction than high-metallicity galaxies in observed GRB host galaxies.

Now we consider the effect of the metal cutoff on the metallicity distribution of the host galaxies. The contribution of  $Z_{\text{gal}} > Z_{\text{crit}}$  galaxies is not zero due to the effect of the internal dispersion. The results with  $\sigma_{Z,\text{int}} = 0.1, 0.3$  and  $0.5$  are shown in Fig. 3. In the cases of  $\sigma_{Z,\text{int}} \geq 0.3$  dex, more than 50% of GRB host galaxies have  $Z_{\text{gal}} > Z_{\text{crit}}$ , suggesting that the progenitor metallicity can be systematically different from the host metallicity.

The contribution of the high-metallicity galaxies ( $12 + \log_{10}(\text{O}/\text{H}) > 8.8$ ) to the cosmic GRB rate is equivalent to that of  $Z_{\text{gal}} < Z_{\text{crit}}$  galaxies when they have  $\sigma_{Z,\text{int}} = 0.5$  dex. In the case of  $\sigma_{Z,\text{int}} = 0.5$  (0.3) dex, roughly 25% (5%) of the host galaxies have  $12 + \log_{10}(\text{O}/\text{H}) > 8.8$ , suggesting the hypothesis that GRBs occur only in low-metallicity environment does not contradict to the recent observations of high-metallicity host galaxies of GRBs. We note that the prediction of the DA08 model is not largely different from that of the late-type galaxy model. The expected mass PDF of GRB host galaxies is shown in the right panels of Fig. 3 in the similar manner to the metallicity PDFs.

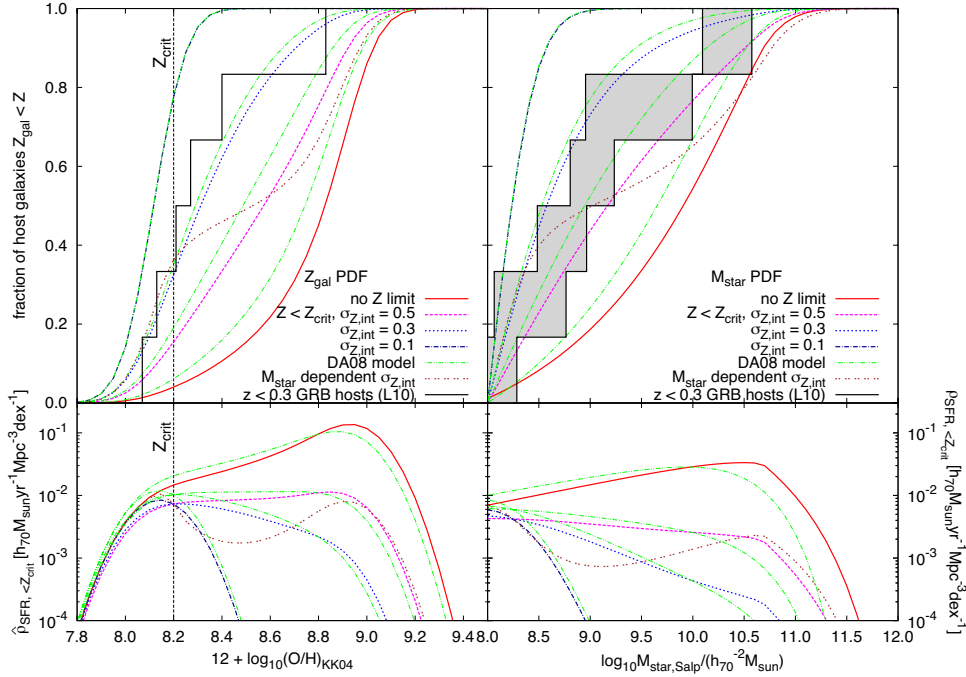
We have assumed that  $\sigma_{Z,\text{int}}$  is same among all galaxies in discussions above. However, the internal metallicity dispersion within galaxies is not well known, and it is possible that galaxies with different  $M_{\star}$  (or  $Z_{\text{gal}}$ ) typically have different  $\sigma_{Z,\text{int}}$ . In fact, the LMC has smaller internal dispersion of metallicity than that in MW (e.g., Rolleston et al. 2002; Cioni 2009). In that case, the expected metallicity distribution would be different from those discussed above. However, the relative contribution of  $12 + \log_{10}(\text{O}/\text{H}) > 8.8$  galaxies compared to the  $Z < Z_{\text{crit}}$  galaxies would be similar to the case of  $\sigma_{Z,\text{int}} \geq 0.3$  dex when high-metallicity galaxies have  $\sigma_{Z,\text{int}}$  comparable to that observed in the MW, regardless of  $\sigma_{Z,\text{int}}$  in  $12 + \log_{10}(\text{O}/\text{H}) \leq 8.8$  galaxies.

To demonstrate a case in which  $\sigma_{Z,\text{int}}$  correlates with  $M_{\star}$ , we employ a toy model of  $M_{\star}$  dependent  $\sigma_{Z,\text{int}}$ ,

$$\sigma_{Z,\text{int}}(M_{\star}) = 0.2 \times (\log M_{\star} - 8.0). \quad (2)$$

The results are shown in Fig. 3. It is interesting that the  $Z_{\text{gal}}$  PDF has multi-peak distribution in this model, although we consider only one population of GRB progenitors.

This bimodality can be explained as follows. In the case of  $\sigma_{Z,\text{int}} = 0.5$  dex,  $\hat{\rho}_{\text{GRB}}(Z_{\text{gal}})$  is approximately constant between  $12 + \log_{10}(\text{O}/\text{H}) = 8.2$  and  $9.0$  (see left bottom panel of Fig. 3). If (1) high-metallicity galaxies ( $12 + \log_{10}(\text{O}/\text{H}) \gtrsim 9.0$ ) typically have  $\sigma_{Z,\text{int}} \sim 0.5$  dex and (2)  $\sigma_{Z,\text{int}}$  is positively correlated with  $Z_{\text{gal}}$ , galaxies with  $12 + \log_{10}(\text{O}/\text{H}) \lesssim 8.2$  or  $\gtrsim 9.0$  have similar  $\hat{\rho}_{\text{GRB}}(Z_{\text{gal}})$  to that in the



**Figure 3.** The  $Z_{\text{gal}}$  PDF (left panels) and  $M_{\star}$  PDF (right panels) of GRB host galaxies predicted in our model. The *top panels* show the normalized PDF, while the *bottom panels* show the  $R_{\text{GRB}}$  weighted metallicity function of galaxies. Observed GRB host galaxies at  $z < 0.3$  (Levesque et al. 2010b, L10) are shown together. The PDFs predicted without the effect of  $Z_{\text{crit}}$  are plotted with red solid lines, while results with  $\sigma_{Z,\text{int}} = 0.5$ , 0.3 and 0.1 dex are shown with dashed (magenta), dotted (blue), and dot-dashed (dark blue) lines, respectively. The green double-dotted dashed line represents the results with DA08 models. The results in the case where  $\sigma_{Z,\text{int}}$  correlates with  $M_{\star}$  are shown with double-dotted line (brown).

case of  $\sigma_{Z,\text{int}} = 0.5$  dex, while smaller  $\epsilon_{\text{GRB}}(Z_{\text{gal}})$  in  $8.2 < 12 + \log_{10}(\text{O}/\text{H}) < 9.0$  produce a dip in the metallicity PDF between  $12 + \log_{10}(\text{O}/\text{H}) = 8.2$  and 9.0. Note that  $\epsilon_{\text{GRB}}$  and  $\sigma_{Z,\text{int}}$  are positively correlated when  $Z_{\text{gal}} > Z_{\text{crit}}$ . Thus it is possible that bimodal distribution of  $Z_{\text{gal}}$  appears from a single population of GRB progenitors, when the conditions (1) and (2) are fulfilled. We should keep in mind that bimodality of GRB host galaxy population does not necessarily mean bimodal nature of GRB progenitors.

#### 4 CORRELATION BETWEEN $Z_{\text{gal}}$ AND SFR

In the previous sections, the dispersions of the  $M_{\star}$ - $Z_{\text{gal}}$  relation and the  $M_{\star}$ -SFR relation are treated independently. However, it is recently claimed that galaxies with higher-SFR tend to have lower- $Z_{\text{gal}}$  compared to lower-SFR galaxies with similar  $M_{\star}$  (Mannucci et al. 2010). Mannucci et al. (2011) and Kocevski & West (2010) have investigated the effect of the SFR- $Z_{\text{gal}}$  correlation on the  $M_{\star}$ - $Z_{\text{gal}}$  relation of GRB host galaxies.

In this section, we use  $M_{\star}$ -SFR- $Z_{\text{gal}}$  relation (Mannucci et al. 2011, hereafter M11 relation) instead of S05 relation, to investigate how the metallicity PDF of the host galaxies is changed if there is a SFR- $Z_{\text{gal}}$  correlation. It should be noted that M11 relation studied in Mannucci et al. (2010, 2011) is calibrated with Nagao et al. (2006, hereafter N06) method. Hence we can not directly compare predictions of M11 relation with predictions and/or observations with KK04 calibration. We project the mass-SFR relation described in § 2.1 to  $M_{\star}$ - $Z_{\text{gal}}$  plane using M11

relation, and compare it with S05 relation. In Fig. 4, one sees discrepancy between the two relation.

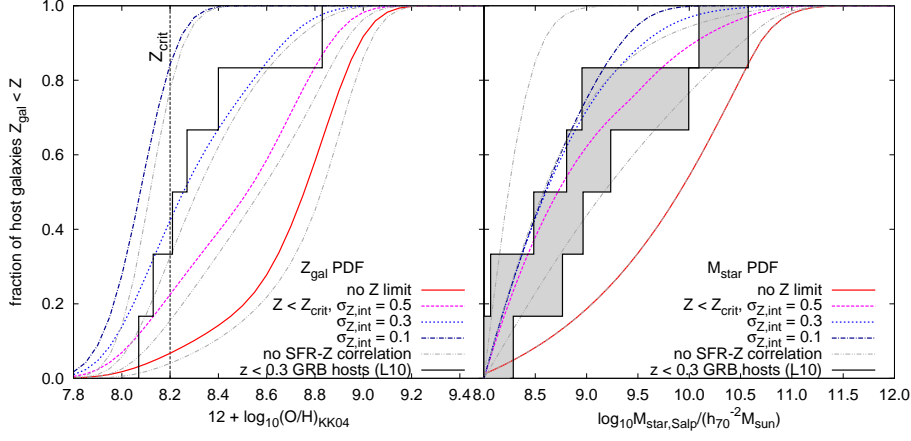
To make consistent comparison between the two models, we assume ad hoc conversion between the two metallicity calibration:

$$\alpha_{\text{KK04}} = \begin{cases} \alpha_{\text{N06}} + 0.25(\alpha_{\text{N06}} - 8.0) + 0.1 & (\alpha_{\text{N06}} < 8.4) \\ \alpha_{\text{N06}} - 0.33(\alpha_{\text{N06}} - 8.4) + 0.2 & (\alpha_{\text{N06}} \geq 8.4) \end{cases}, \quad (3)$$

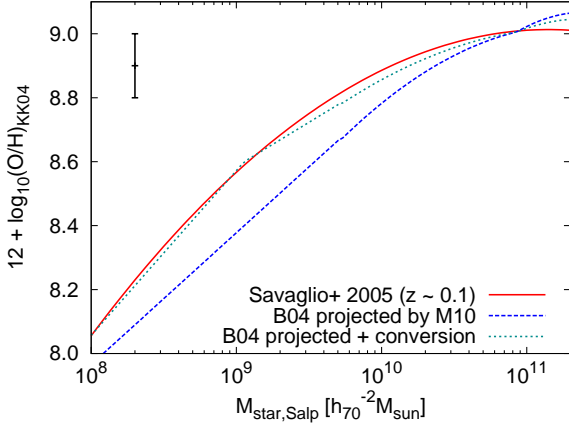
where  $\alpha$  represents  $12 + \log_{10}(\text{O}/\text{H})$ . Converted with Eq. 3, the projected  $M_{\star}$ -SFR relation agrees with S05 relation in 0.04 dex (Fig. 4).

The metallicity and mass PDFs predicted using M11 relation are shown in Fig. 5. Although the host galaxies have lower-metallicity by  $\lesssim 0.1$  dex compared to the case of S05 relation depending on  $\sigma_{Z,\text{int}}$ , M11 relation alone does not make the metallicity PDF consistent to the current sample of GRB hosts without further metallicity effect. The metallicity PDFs with the metallicity cut-off may agree with the observations, as well as in the case of S05 relation.

The predicted host galaxies in the case of  $\sigma_{Z,\text{int}} = 0.5$  have smaller  $M_{\star}$  compared to that for S05 relation, while the host galaxies in the case of  $\sigma_{Z,\text{int}} = 0.1$  have larger  $M_{\star}$ . As a result, the mass PDF is less sensitive to the change of  $\sigma_{Z,\text{int}}$ . This is because SFR and  $Z_{\text{gal}}$  correlate stronger when  $M_{\star}$  is smaller in M11 relation. Once a galaxy sample is weighted with SFR, M11 relation makes  $M_{\star}$ - $Z_{\text{gal}}$  relation steeper, and hence a difference in  $Z_{\text{gal}}$  corresponds to smaller difference in  $M_{\star}$  with M11 relation compared to the case with S05 relation. However, we note that the predicted mass PDF is strongly dependent on the low-metallicity tail of M11 relation, which is still highly uncertain.



**Figure 5.** Same as the top panels of Fig. 3, but M11 relation is assumed instead of S05 relation. The results with S05 relation, which have been shown in Fig. 3, are plotted together (grey double-dotted dashed lines).



**Figure 4.** The  $M_{\star}$ – $Z_{\text{gal}}$  relation of low-redshift galaxies ( $z \lesssim 0.3$ ) presented in Savaglio et al. (2005, S05 relation, the red solid line) is compared with the mass–SFR relation (Brinchmann et al. 2004) projected by M11 relation (Mannucci et al. 2011, blue dashed line). The conversion of the projected  $M_{\star}$ –SFR relation with Eq. 3 is shown with a cyan dotted line.

## 5 DISCUSSIONS

We have predicted the metallicity and mass PDFs of GRB host galaxies, assuming empirical formulations of galaxy properties and the model of GRB rate in which GRBs occur only from low-metallicity stars ( $< Z_{\text{crit}}$ :  $12 + \log_{10}(\text{O}/\text{H}) = 8.2$ ). Our results show that  $> 50\%$  of GRB host galaxies can have  $Z_{\text{gal}} > Z_{\text{crit}}$ , and high-metallicity galaxies ( $12 + \log_{10}(\text{O}/\text{H}) \gtrsim 8.8$ ) may have significant contribution to cosmic GRB rate. This means that metallicities of GRB host galaxies may be systematically different from those of GRB progenitors, and the low-metallicity scenario can be reconciled with the observations of high-metallicity host galaxies of GRBs.

For some GRBs, metallicities are measured at the positions of the bursts (e.g., Modjaz et al. 2008), and the host galaxy of GRB 020819 has high-metallicity at the position of the burst (Levesque et al. 2010a). However, it should be noted that the positioning error of GRB 020819 is roughly

5 kpc (Jakobsson et al. 2005), and there might be chemical inhomogeneity in the error circle. We need more precise localization of GRBs to draw robust conclusions, although it is also difficult to specify what precision is required. The required precision is dependent on the mixing process of inter-stellar medium which is not well understood.

Although we have formulated  $\epsilon_{\text{GRB}}(Z_{\text{gal}})$  motivated by the probable chemical inhomogeneity within each GRB host galaxy, similar formulation of  $\epsilon_{\text{GRB}}(Z_{\text{gal}})$  may be obtained considering other effects (e.g. moderate low-metallicity preference of GRB occurrence without sharp metallicity cutoff). It is currently difficult to distinguish what effect constructs  $\epsilon_{\text{GRB}}(Z_{\text{gal}})$ .

We have shown that multi-peak distribution of the metallicity of GRB host galaxies can be produced by a single population of GRB progenitors, when  $\sigma_{Z,\text{int}}$  positively correlates with  $M_{\star}$ . If observed, the bimodality can be a clue to investigate the nature of GRB progenitors. If  $\epsilon_{\text{GRB}} > 0$  in high-metallicity galaxies is caused by the nature of GRB progenitors rather than properties of galaxies, there would be no effect of the  $\sigma_{Z,\text{int}}$ – $M_{\star}$  correlation.

Although some results shown in this paper suffer from uncertainties about the properties of low-redshift galaxies, some important features of the results which we have discussed are not dependent on the detail of the modelings (see § 3). However, we need to understand the actual metallicity distribution within young star forming galaxies to make reliable prediction of the exact metallicity PDF. More detailed study of the internal structure of galaxies requires different approach from that in this study, such as high-resolution hydrodynamic simulation and/or spatially resolved spectroscopic observation of large sample of galaxies, and we address this issue to future studies. Future development of our knowledge about galaxy properties would provide us with more robust predictions about GRB progenitors and their host galaxies.

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